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Inter-annual rainfall variability may foster lake regime shifts: An example from Lake Bourget in France

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ABSTRACT

The Intergovernmental Panel on Climate Change anticipates increasing extreme rain events in the 21st century, leading to more frequent floods and more phosphorus transported into lakes, enhancing the risk of their eutrophication. This paper reports research assessing this risk on Lake Bourget in France, by coupling a statistical estimation of annual phosphorus transportation from annual rainfall and a dynamical model estimating the evolution of the phosphorus concentration in the lake in the period 2000–2050 according to yearly phosphorus transportation. The study of the model on the past suggests that the relative drought of the 2000s has fostered the effect of management measures to reduce phosphorus loading, enabling compliance with the Organisation for Economic Co-operation and Development guidance target for 2020. Simulations on different scenarios for the future show that a 10% increase in the rainfall standard deviation nearly doubles the probability of eutrophication, from 2.40% to 4.26% between 2016 and 2050.

1. Introduction

Human activities often disrupt the dynamics of ecosystems (Folke et al., 2004; Johnson and St-Laurent, 2011). Discharges from agricultural spraying and industrial waste which find their way into tributary waters may cause lakes to shift from oligotrophic to eutrophic state, where clear water becomes turbid due to algal blooms favored by excessive phosphorus (P) concentration (Carpenter, 2005; Sharpley, 1993; Pote et al., 1996). Lake eutrophication has substantial economic costs (Bennett et al., 1999; Carpenter et al., 1998). For instance, losses attributed to lake-front property values and recreational use of United States of America freshwaters were put at approximately $2.2 billion a year (Dodds et al., 2009). Moreover, reducing P intake is not always enough to recover oligotrophic state, and some cases require additional interventions on lake internal mechanisms (NRC, 1992). However, these operations are not always effective or feasible, and may be difficult in practice, as shown by the relapse of the bio-manipulated Lake Zwemlust in the Netherlands six years after its cleaning (Van Donk and Gulati, 1995). Climate change directly impacts eutrophication (Jeppesen et al., 2007; Scheffer and Carpenter, 2003). For instance, rising temperatures fosters rainfall instead of snowfall during winter, causing greater soil leaching which has implications for the magnitude of P transport (Woodbury and Shoemaker, 2013; Górniak and Piekarski, 2002). However, interactions between climate change and eutrophication are complex, and projections are somewhat contradictory as climate-influenced processes have interacting and often opposing effects (Fig. 1). A temperature increase would intensify P diffusion from deep sediments, but also increase P sedimentation, and these two flows may have compensatory effects on P concentration (Bryhn et al., 2010). Changes in temperatures and wind may have compensatory effects, with a modest overall impact on P concentration.

According to the IPCC, the frequency of heavy rainfall is likely to increase (IPCC, 2013). Some studies have been done on the role played by the rainfall variability in dryland plant ecosystems (Borgogno et al., 2007), African savannas (Synodinos et al., 2018) or Australian reservoir (Linden et al., 2004). Rainfall variability could affect water quality by increasing pollutant loads flushed into rivers due to soil erosion. When there is the potential for floods, land use becomes a key driver of P loading to lakes (Fraterrigo and Downing, 2008). Intensive rainfall could significantly increase the risk of eutrophication due to higher P leaching from manure application (Xue et al., 2013). When external inputs are the main form of loading, such as in agricultural watershed, rainfall is a key driver of P transport (Correll et al., 1999). Since drought periods will be drier and wet periods will be wetter (Arnell et al., 2014), inter-annual variability in rainfall is set to increase.

The main aim of the paper is to evaluate the effect of one proxy of climate change (rainfall) on lake eutrophication. Specifically, the impact of inter-annual rainfall variability on the quality of the lake water

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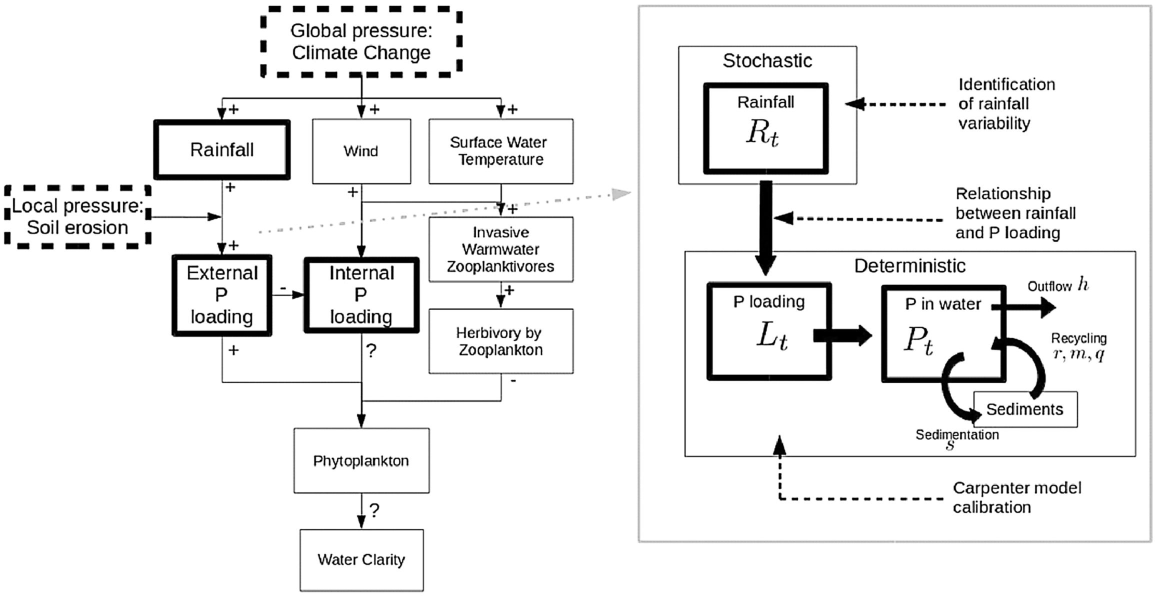

Fig. 1. Left: Diagram of interactions between climate change, lake and watershed processes, and water clarity of a lake, Adapted from the IPCC (McCarthy and Intergovernmental Panel on Climate Change, 2001): "+" means an increase and "–" means a decrease in the process; "?" means contentious expectations. Blooms depend on external and internal P loading. Wetter climates or more episodic rains lead to more external P loading. Right: Phosphorus model (adapted from Carpenter and Brock (2006)). The dotted arrows exhibit the main contributions of the paper. By the relationship between rainfall and P loading, repercussions of rainfall variability on the deterministic P model are analyzed.

is studied. In what follows, the variability in rainfall is characterized by an increase of rainfall standard deviation, with mean rainfall remaining the same. For this purpose, two relationships are clearly defined: "rainfall–P loading" and "P loading–P concentration in the lake". These relationships are modeled and calibrated on the data from Lake Bourget in the French Alps. Once the models are calibrated, two prospective scenarios are analyzed: a low rainfall variability (equivalent to the rainfall variability in the 20th century) and an increase of inter-annual rainfall variability as suggested by the IPCC (Arnell et al., 2014). For each scenario, the dynamics of P concentration in the lake until 2050 is calculated. Results show that low rainfall variability has limited effects on the probability of eutrophication in the short and long term. However, projections show that a 10% increase in rainfall variability increases the probability of eutrophication from 2.40% to 4.26% between 2016 and 2050.

2. Methods

2.1. Lake Bourget: case study of eutrophication mitigation

Lake Bourget is the biggest lake located entirely within France. The lake is located in the French Alps at the southernmost end of the Jura Mountains in the department of Savoie (latitude 45°44′N, longitude 5°52′E). Its maximum length is 18 km and its surface area is 44.5 km^2. The water volume is 3.6×10^9 m^3. The lake's mean depth is 80 m and its maximum depth is 147 m. The epilimnion ranges from 0 m to 10 m, while the hypolimnion ranges from 80 m to 140 m. The water residence time is about 14 years. Two main tributaries flow into the lake: the Leysse river and the Sierroz river. They are responsible for 80% of the water inflow. The three smaller inflows are the Tillet, the Belle-Eau, and Chautagne canal. The primary outflow is the Savières canal flowing into the Rhône, which also minimally contributes to the incoming flow (Jacquet, 2015). Lake Bourget's catchment is largely composed of forest and semi-natural areas (48%). Furthermore, 32% of the catchment area is being used for agriculture activity which is the main source of P loading (Magni and Chinaglia, 2008). The watershed area is about 560 km^2 including the urban areas of Aix-les-Bains and Chambéry. Lake Bourget has suffered heavy P discharges since the 1960s, leading to its eutrophication (Vincon-leite et al., 1995). In 1974, the amount of incoming P in the lake reached 300 tons annually. Several measures have since been taken to reduce the eutrophication of Lake Bourget (Vinçon-Leite et al., 2006; Rivera Rocabado Jacquet et al., 2017). The main objective was to reduce P loading to 30 tons per year and keep P concentration in the lake under a threshold of 10 μg L^{-1} (i.e. 36 tons of P in the lake, considering the lake volume as a constant) in order to limit eutrophication. In particular, a 12-km gallery treating effluent station was set up in 1980 in order to prevent the effluents of water treatment plants to be rejected into the lake. This measure lightens the mass of P ending up in the lake. The last major project to date is the construction of a polluted-water retention basin.

Lake Bourget is monitored by the Comité Intersyndical pour l'Assainissement du Lac du Bourget (CISALB), the intersyndical committee to clean up the lake, which regularly collects physical-chemical data by measurements made in different places of the lake. The samples are taken far from the main tributaries, at different levels of depth. The annual in-lake P concentration is estimated by the P concentration during the winter mix, when the temperature of the water column is homogeneous. In addition, the tributary monitoring stations upstream of the lake record P loading concentration (Fig. 2). The Sierroz and the Leysse account for the majority of P loading. To complete incoming balances, the CISALB takes into account the P from the Tillet (about 5% of total volume transited to the lake) and direct discharges to the lake, including the discharge of mixed water by the Aix-les-Bains combined sewer to the storm overflow of Biâtres. The meteorological data comes from the Meteo France station located at the south end of the lake. Since 2004, annual reports give the data used in this work, summed up in Table 1.

The ecological state of the lake today is healthy, progressing towards being oligotrophic. Measurement surveys give 150 tons of incoming P in 1983 and 94 tons of incoming P in 1994–1995. Lake Bourget is a successful example of re-oligotrophication, since P mass has been lower than 60 tons from the early 2000s. Despite the current good ecological state of the lake, some elements undermine the CISALB results. Frequent blooms of toxic cyanobacteria (Plantothrix rubescens) appear, and a Microcystis bloom was observed in 2014. This suggests that the current state of the lake is unstable (Jacquet, 2015). Indeed, adverse weather conditions may load P to the lake and exceed the

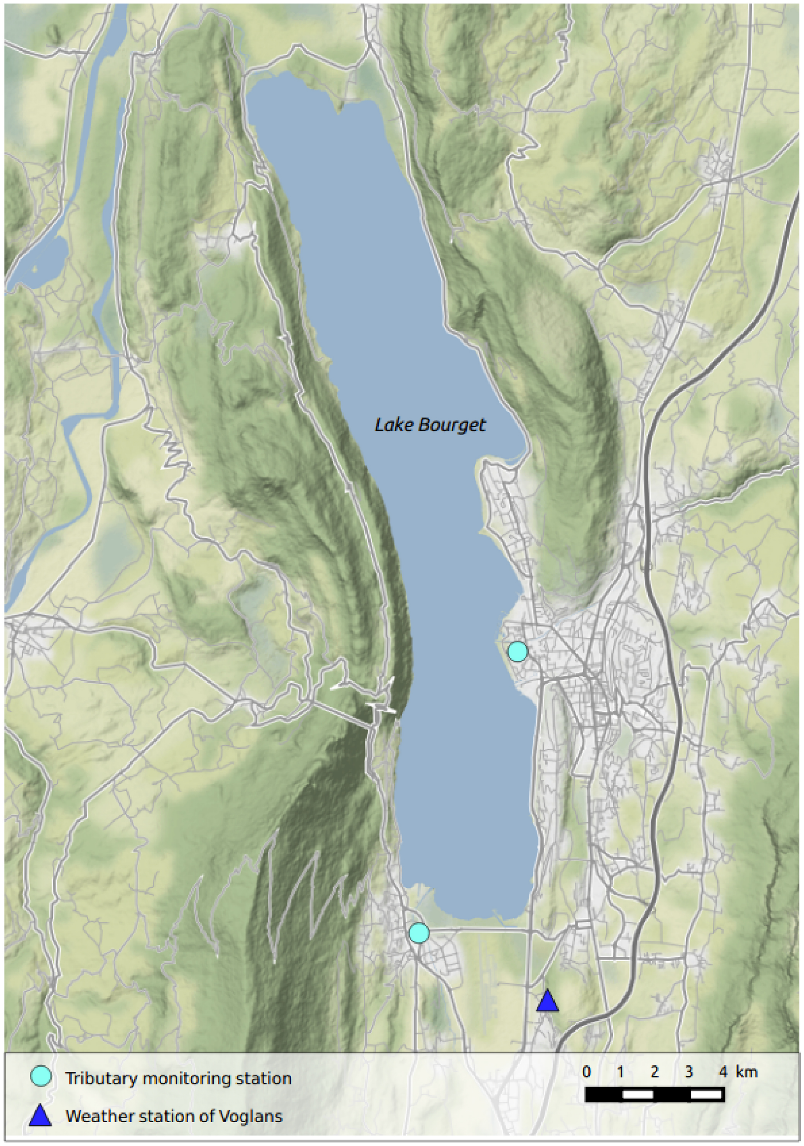

Fig. 2. Lake Bourget map.

Table 1
Avalaible data. Rainfall level, P loading and in-lake P concentration from 2004 to 2016. The in-lake P mass is estimated from the in-lake P concentration and the water volume.

Year	Rainfall level, R_t (mm)	P loading, L_t (tons)	In-lake P concentration (µg L^{-1})	In-lake P mass, P_t (tons)
2004	1027	48	33	118.8
2005	888	28	31	111.6
2006	1004	25	24	86.4
2007	1238	32.8	22	79.2
2008	1214	18.2	20	72
2009	929	13.7	20	72
2010	1031	20.4	17	61.2
2011	1079	26.8	16	57.6
2012	1372	40.3	14	50.4
2013	1467	52.8	11	39.6
2014	1231	42.1	11	39.6
2015	1322	57.1	10	36
2016	1181	34.4	8	28.8

regulatory threshold. In addition, the mechanics of lag release of P stored in sediments may also deteriorate the state of the lake.

2.2. Modelling the relationship between rainfall and P loading in the lake

Since the beginning of the 2000s and the end of major measures to clean up the lake, P loading has stagnated. CISALB studies show that over 90% of P loading is as a result of rainfall events, with over 50% of P loading brought by the main floods. These floods cause soil leaching where P is transported from fertilized agricultural soils to surface water via flowing water, which explains the unusually high P concentrations in the water during these periods. Annual rainfall may be used as an indicator of P loading, as changes in rainfall lead to changes in P loading.

The Pearson correlation between annual rainfall and P loading on data from 2004 to 2016 is 0.66, showing a good degree of linear dependence, as shown in Fig. 3. This correlation leads us to suppose that soil leaching in times of rain is the major source of P loading. The study of Lake Champlain, which is also subject to Microcystis blooms, also shows a strong correlation between rainfall and P loading (Fortin et al.,

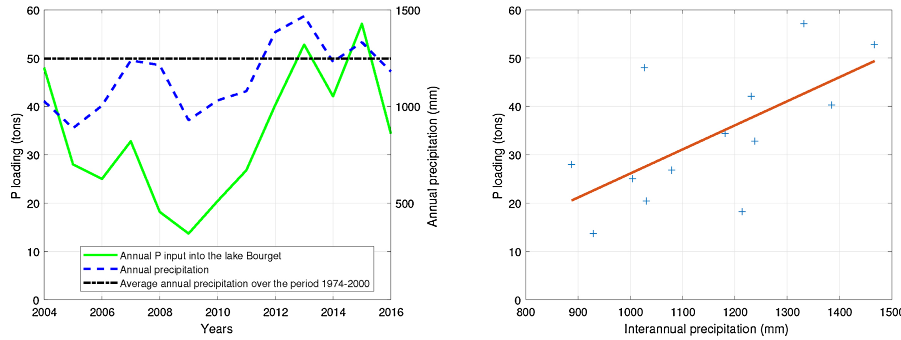

Fig. 3. Left: The left axis measures annual P loading into the lake. The right axis measures the rainfall at Voglans meteorological station. Right: Correlation between rainfall and P loading. Data are from annual reports for 2004–2016.

2015). The recent period of low rainfall and decrease in P input confirmed the correlation between P and rainfall.

The main sources of P are the inflowing streams coming from the Leysse and the Sierroz rivers. This study neglects diffuse soil P which ends up in the lake. A linear model is applied, as in Ockenden et al. (2016) who found a strong linear relationship between total rainfall and total P load in catchments, suggesting that the non-linear effects are small compared to the variability in event rainfall. The P loading at year t, is denoted L_t, and can be written as a linear function of rainfall level at year t, denoted R_t:

$$L_t = \alpha R_t + \beta \tag{1}$$

The CISALB annual reports (Rivera Rocabado Jacquet et al., 2017) give annual P loading and annual rainfall from 2004 to 2016. P data before 2004 is difficult to exploit, because of the sparsity of the studies, and therefore is not taken into account in this study. A linear regression gives the parameters α and β of the relationship between rainfall and P loading. Rainfall is assumed to follow a normal distribution based on the measures from 2004 to 2016 ($\mu_R = 1154$ and $\sigma_R = 178.2$). The hypothesis of a normal distribution is rejected neither by the Lilliefors test ($p = 0.68$) nor by the Jarque-Bera test ($p = 0.59$).

2.3. Modelling the eutrophication dynamics

With the relationship between rainfall and P loading in the lake established, the impact of P loading on in-lake P concentration can then be assessed through modeling. Many models study P dynamics by separating epilimnion from hypolimnion dynamics (Lung et al., 1976) and the different P phases (Malmaeus and Håkanson, 2004). Some of them were built for a specific lake and are not reusable without the same set of parameters (Vigiak et al., 2012). A monthly dynamical model developed for Lake Bourget yields concentrations and flows in three water layers (Bryhn et al., 2010). This study presents a model that incorporates an annual P dynamics developed by Carpenter et al. (1999) and used in Rougé et al. (2013). Two state variables are used: the whole mass of P present in the lake, noted P, and P loading, L (Fig. 1). The model is built from the analogous equation for P:

$$\frac{\mathrm{dP}}{\mathrm{dt}} = L - (s + h)P + r\frac{P^q}{P^q + m^q} \tag{2}$$

where s is rate of sedimentation, h is rate of out-flooding P, r is maximal mass of P recycled by sediments, q is the exponent of the recycling curve, depending on the type of the lake, and m is the P mass for which recycling reaches half of the maximal rate. There are interactions between these processes, so the differential equation has to account for the possibility of several sedimentation and recycling events during a single year. The mass of P in the lake at $t + 1$, P_{t+1} is obtained as a function of P_t and L_t by using the MATLAB function *ode45*, based on an explicit Runge–Kutta (4,5) formula.

The reports available give annual P in the lake, and annual P loading is estimated from rainfall R according to the linear model. The outflow rate h is supposed to be fixed at $0.12\ \mathrm{yr}^{-1}$. The parameters s, r, q and m are calibrated by using an exhaustive training/validation method avoiding over-fitting. The 12 data points (P_t, R_t, P_{t+1}) between 2004 and 2015 are divided into two sets: a training set (7 points) and a validation set (5 points). The training set is used to calibrate the model (by using the MATLAB function *lsqcurvefit*). The root mean squared error (RMSE) between the validation set and the projections is computed. The parameters that minimized the RMSE onto the validation set among all couple of training/validation sets is selected.

3. Results

3.1. Model calibration

For the relationship between R_t and L_t, the calibration gives $\alpha = 0.0498$ and $\beta = -23.693$ with a global RMSE of 10.7. The p-value is 0.0151. For the annual P dynamics, the following parameters are obtained and summarized in Table 2: $s = 2.1476\ \mathrm{yr}^{-1}$, $r = 367.04\ \mathrm{tons{\cdot}yr}^{-1}$, $q = 2.222$, and $m = 96.85$. The training set (2004, 2005, 2008, 2010, 2012, 2013, 2014) and the validation set (2006, 2007, 2009, 2011, 2015) minimize the RMSE on the validation dataset (6.28). The percent PBIAS on these training/validation sets is $+2.3239\%$ indicating a slight overestimation bias. The exponent q is in agreement with Carpenter et al. (1999), because q is close to 2 for deep lakes but around 20 in a shallow lake. Using the full model (Eqs. (1) and (2)), P concentrations are simulated from 2004 to 2016, using only the data from 2004 and the rainfall data from 2004 to 2016 (see Fig. 4). Measured and projected in-lake P level showed good agreement corroborating the use of P loading as a linear function of rainfall level.

3.2. Tipping points warning

P level in the lake has continued to decrease since the early 2000s. OECD norms consider the state of the lake as oligotrophic if in-lake P level is below 40 tons. This P threshold is calculated from the Vollenweider model (Paris, 1982) that can be readily used by managers and technical personnel with limited limnological knowledge. Studying

Table 2
Parameters calibration.

Parameters	Value
α	0.0495
β	−23.693
s	$2.1476\ \mathrm{yr}^{-1}$
h	$0.12\ \mathrm{yr}^{-1}$
r	$367.04\ \mathrm{tons{\cdot}yr}^{-1}$
q	2.222
m	96.85

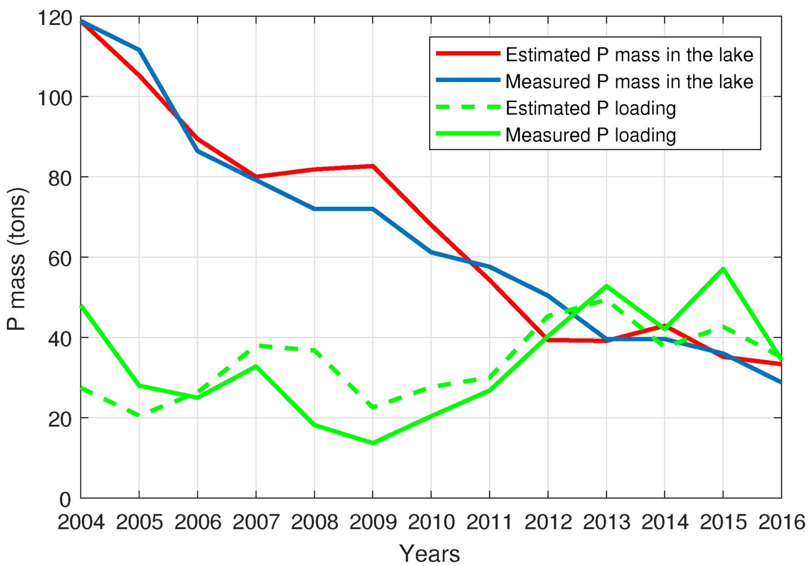

Fig. 4. Time-course of P level in Lake Bourget from 2004 to 2016. Estimated P mass (red line) in the lake is computed from the P model and estimated P loading (green dotted line) from the rainfall model (Eq. (2)). Measured P levels are shown in blue (P mass in the lake) and green (P loading). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the equilibrium states of our model provides information on the risks of coming close to a tipping point (Fig. 5). The precipitation/P representation is interesting in terms of management, as the recorded rainfall is generally more accessible indicator than P loading. The stability of the low equilibrium declines as rainfall R approaches 1402 mm, because the bifurcation point is approached. When $R = 1402$ mm, the concentration of P jumps to high values. Once the mass of P in the lake has reached high values of equilibrium, rainfall has to be below $R = 1196$ mm to recover low equilibria. If rainfall does not decrease, the transition can be irreversible. The OECD norm on maximum P in the lake fits well with the model which gives a threshold of 42 tons. This threshold corresponds to the boundary between oligotrophic states and mesotrophic states. In addition, a second threshold (89 tons) is fixed, above which the amount of P in the lake is in the range of the upper equilibria, corresponding to the boundary between mesotrophic and eutrophic states.

3.3. Impact of rainfall variability on P trajectories

3.3.1. A relative drought accelerates the decrease of phosphorus concentration in the lake

In 2015, the level of P in the lake reached the OECD threshold. This study investigates the role of the 2004–2011 drought on this result. For this purpose, potential lake trajectories are computed starting from 2004 according to the annual loading hazards. The input of the model each year are P present in the lake in the previous year and P loading drawn randomly from rainfall distribution which is normal with $\mu_R = 1154$ and $\sigma_R = 178.2$, based on the 2004–2016 measures. The time-series of P_t and R_t then represent the lake's trajectory. Results are reported in Fig. 6. The main result is that current P concentration is lower than the median P concentration in 2016 forecasted by the model, which suggests that this recent drought helped improve the water quality. Consecutive years of low rainfall have allowed the

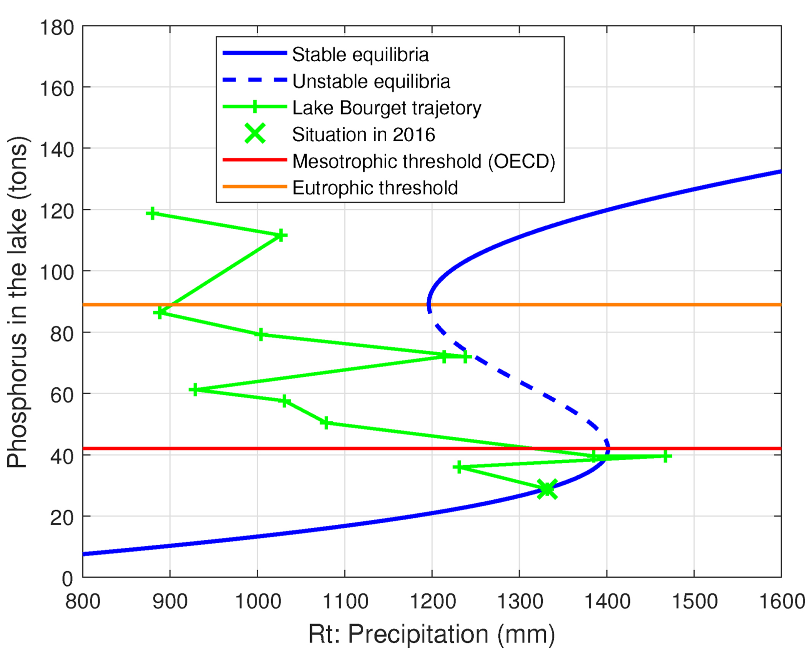

Fig. 5. Bifurcation diagram. Equilibria are shown in blue, and trajectory of Lake Bourget from 2004 to 2016 in green. The threshold separating mesotrophic and oligotrophic states is shown in red. For this lake, the threshold in orange defined which state of the lake is eutrophic. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

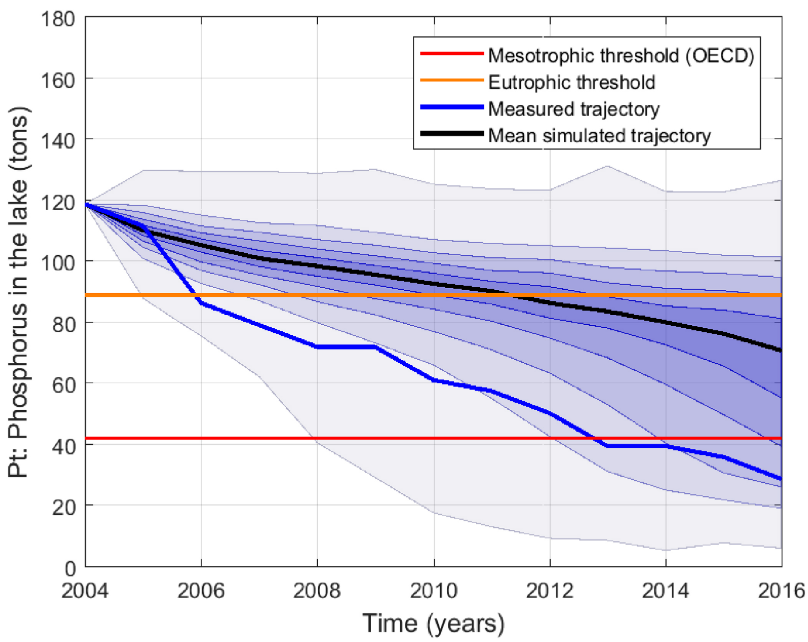

Fig. 6. Running the model from 2004. A set of 1000 trajectories has been computed. The time-varying distribution deciles are shown as shaded bands around the median trajectory (black line). The blue line shows measured trajectory. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dynamics of the lake to rapidly reach the low equilibria. P loading level and P present in the lake are on a trajectory to reach the CISALB recommended values qualifying the state of the lake as oligotrophic.

3.3.2. Long-term projection: scenario of change in rainfall variability until 2050

Here the correlation between rainfall and P loading is used to study the potential impact of increased rainfall variability on the state of the lake. A change in the inter-annual rainfall variability results in a change of standard deviation of P loading. Two scenarios are studied:

- the nominal scenario in which rainfall R follows a normal distribution with the same standard deviation $\sigma_R = 206$ as in the 1974–2016 period.
- The high rainfall variability scenario with a linear increase of 0.294% per year of σ_R which means a rise of 10% in 2050. This scenario is built for highlighting the increased risk of extreme events caused by climate change (Arnell et al., 2014). A greater inter-annual rainfall variability thus illustrates the succession of years of severe drought and years of high floods.

For both scenarios, annual mean rainfall level is assumed to be the same (i.e. $\mu_R = 1248$). It corresponds to the average of inter-annual precipitation for the 1974–2016 period. The higher rainfall intensity on wet days offsets the decrease in number of these days observed in Europe, which results in a negligible change in expected annual rainfall amount (Dankers and Hiederer, 2008), and allows us to focus on the impact of inter-annual variability in rainfall. The parameters of these scenarios are summarized in Table 3. After running the model, the probability of the nominal scenario leading to lake eutrophication is about 2.40% in the long term. Cleaning operations conducted by the CISALB made the lake strong enough to withstand disturbances, since median P in the lake is around 25 tons after 2020 according to both scenarios (Figs. 7 and 8).

3.3.3. Potential instability due to changes in rainfall variability

Table 3 reports the mean residence time in each of the three domains according to scenario. On average, the P influx during rainy weather is not sufficient to shift the lake from a mesotrophic or oligotrophic regime to a eutrophic regime. The dynamics tends to stabilize the in-lake P towards low equilibria.

However, increasing the inter-annual rainfall variability increases the risk of seeing the state of the lake being drawn to the high equilibria. Change in variability affects the probability of reaching the eutrophic domain from 2.40% to 4.26%. The probability of eutrophication, although low, increases significantly between the two scenarios. Therefore, with several consecutive years of high rainfall, the dynamics may lead to a eutrophic regime (Fig. 8). Likewise, this phenomenon can be reversed by years of drought: the dynamics leads the state of the lake towards the low equilibria.

4. Discussion

There are mitigation strategies to limit the consequences of soil leaching during consecutive years of wet weather. The main option is to create an interface to limit direct P discharges from farms. Numerous wetlands including sedimentation basins or infiltration basins make potential interfaces (Schoumans et al., 2014). Having a buffer zone (or ‘riparian buffer’) acting as a filter and capturing P in runoff may be effective to enhance water quality (Borin et al., 2005). The retention efficiencies vary from 36–70% from forested buffers to 73–79% from combined grass and woody buffers (Hawes and Smith, 2005).

Effective measure would be to avoid fertilizer application when

Table 3
Long-term rainfall scenarios. Parameters of each scenarios and mean time in each domain according to each scenario, based on 10,000 trajectories between 2016 and 2050. The probability of reaching the eutrophic domain is also computed.

	Nominal rainfall variability scenario (scenario 1)	High rainfall variability scenario (scenario 2)
Rainfall mean, μ_R	1248	1248
Rainfall standard deviation, σ_R	206	from 206 in 2017 to 226.6 in 2050 (+10%)
Mean time in the oligotrophic domain	≈17.1 years	≈15.4 years
Mean time in the mesotrophic domain	≈8.49 years	≈8.64 years
Mean time in the eutrophic domain	≈8.43 years	≈9.95 years
Probability of reaching the eutrophic domain	≈2.40%	≈4.26%

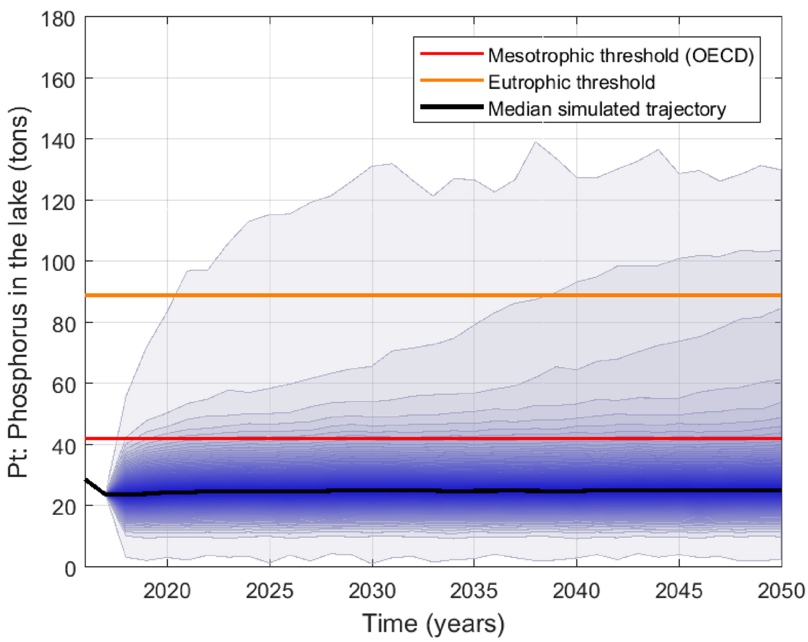

Fig. 7. Forecast fan chart according to the current variability rainfall scenario. 10,000 trajectories are simulated starting from 2016 until 2050 according to the high-variability rainfall scenario. The time-varying distribution centiles is shown as shaded bands around the median trajectory. The median trajectory (black line) is below the mesotrophic threshold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

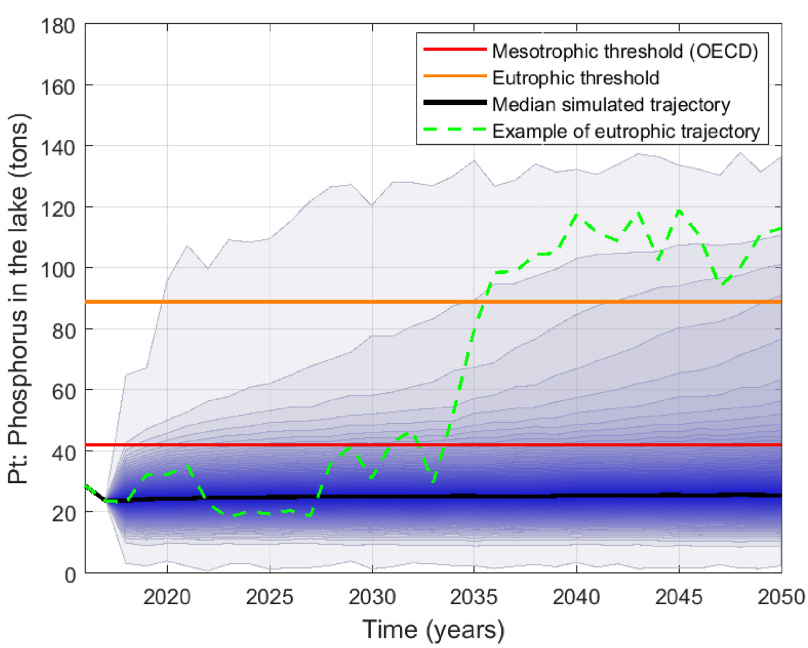

Fig. 8. Forecast fan chart according to the high-variability rainfall scenario. 10,000 trajectories are simulated starting from 2016 until 2050 according to the high-variability rainfall scenario. The time-varying distribution percentiles is shown as shaded bands around the median trajectory. While the median trajectory (black line) is below the mesotrophic threshold, the high variability of P loading increases the number of trajectories reaching the eutrophication threshold (horizontal orange line). Example of extreme trajectory leading to a regime shift (dashed green line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

heavy rain is likely (Hoffmann et al., 2009). Other changes in land use (Schoumans et al., 2014), such as avoiding high-intensity tillage may protect lake tributaries against from receiving P losses from agricultural soils (Hansen et al., 2000). However, exploratory models have shown that situations with high natural variability could lead farmers to use P more intensively (Janssen, 2001), as global change sharpens the pressure on farms to be profitable (Ekholm and Lehtoranta, 2012). Therefore, in addition to rainfall variability, the mitigation measures and the practices in the farms also need to be taken into account.

Our model does not include these possible evolutions at farm level and its quantitative results should be considered with caution also because it is based on a small dataset. However the observed qualitative trend is clear. In the long term, an increase in rainfall variability is likely to increase the probability of eutrophication. The model could be improved by calibrating it on a larger series of data, whose availability is a classic challenge in ecosystem management, or by adding mechanisms such as the passive diffusion of P from soil. Other variables may also be included in the model, such as chlorophyll a or luminosity. It might also be relevant to develop a model that would account for other effects of climate change, such as surface water temperature variations which affect the development of algal blooms in summer periods. Furthermore, a time step smaller than the year may give relevant additional information on the system. For instance, a monthly model could account for the temporal distribution of floods during the year. Indeed, two rainy events close in time do not leach the soil like the same two events separated by a long interval (Merceron, 1999)

5. Conclusion

The effect of increasing the variability of inter-annual rainfall on the eutrophication of Lake Bourget has been investigated. A dynamical model of P concentration in the lake is studied, where its equilibria help determine trophic thresholds. The probability of lake eutrophication is assessed by running a large number of simulations with sequences of

rainfall at variability levels, drawn at random. Short-term simulations showed a stabilization of lake state below the OECD recommendations, and suggest that the recent drought favoured this stabilization process. In the long term, an increase in rainfall variability is likely to increase the probability of eutrophication.

Finally, the approach adopted here can be adapted to other socio-ecological systems in order to evaluate how the increasing frequency of extreme events impacts the services that these systems provide.

Acknowledgements

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